Air Mag: Pneumatic Actuation and Sensing Methods to Enrich Interactivity and Wearability of Foot Wearables

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Abstract

This works presents Air Mag, a foot wearable that uses pneumatic actuation and acoustic sensing for a wide range of foot interactions. With wearable devices such as smartwatches becoming increasingly popular, we aimed to explore the possibilities of increasing the interactivity of a shoe, a much more popular wearable associated with being on the go. Using a known air pouch fabrication technique to construct airtight sealed pouches, we introduce a device that uses a pneumatic actuation system to rapidly deflate and inflate air pouches, providing a tightening sensation to the end-user. We also use a known acoustic sensing technique to detect the deformation of the air pouches in real-time using a microphone and speaker. Our results show several advantages and limitations of using such methods in the context of foot wearables and introduce future development of our wearable. Such a device can serve as a novel method for gait recognition, create toe input gestures, or be used as a tangible interface for haptic feedback.

Introduction

Human-computer interaction (HCI) is a field within computer science centered around the interactions between humans and computers. Research in the field has helped popularize handheld wearables such as smartwatches and foot wearables in the medical industry [1]. However, still less than half the US population uses smartwatches, while most of the population wears shoes [2]. Nike has recently introduced motorized self-lacing shoes that are not only convenient for end-users, but have also proven to have higher foot containment than standard shoes while performing multiple tasks [3]. Reebok's InstaPump shoes feature an alternative shoe tightening method in which pouches in the tongues of the shoe are inflated via manual pumping [4]. Inspired by these shoes, we introduce a foot wearable device that uses pneumatic actuation and acoustic sensing for a wide range of foot interactions.

We fabricated air pouches and placed them inside the shoe's tongues for automatic inflation, using a pneumatic actuator as opposed to Reebok's manual pumping system. Air pulses have recently been exploited to enable interactive input in objects via acoustic sensing methods [5,6], so we aimed to detect the pouch's deformation using a connected speaker-microphone pathway. Such a working device would have many potential applications including input gestures, gait recognition, and notification systems. For example, the particular way that inflated pouches placed on the toes deform from moving a specific toe could be a novel method for creating toe input gestures. The unique way a user’s pouches deform while they’re walking could be a novel method for gait recognition. A small air pulse can be sent to a pouch placed near a more sensitive area of the foot such as the sole to notify a user of something. Therefore, our project’s main goal is to successfully create the foot wearable. Upon hopefully successful creation, it will then be easy to explore and select several useful applications.

Literature Review

Recently, pneumatic actuation has been introduced for various interactive media applications. Niyama et al. [7] introduce an interactive interface implementation using air pouches. The air pouches are constructed using a 3D printer with a soldering iron attached to the belt as opposed to the extruder. The soldering iron heat bonds two thermoplastic sheets together to form pouches. When attached to various everyday objects, inflation and deflation of the air pouches cause actuation, allowing for simple manual and programmable control systems. We built this same fabrication machine in order to automate precise fabrication of the air pouches we will use in our foot wearable. The inflation of these air pouches placed in the wearable provides the tightening sensation for the end-user, so it is critical that they are consistently sealed airtight by the soldering iron.

Sareen et al. [8] show a much larger scaled air pouch fabrication technique to design inflatable objects such as furniture as a single component. The fabrication technique introduces the use of folds before sealing, allowing for greater air pouch flexibility. Swaminathan et al. [9] present truss design primitives to implement active room-scale structures that respond to user input. Air pouches are constructed using a customized heat sealing printer and used as the frame of the structure. Multiple sensing methods are selected to add interactivity of the pouches, including capacitive, swept frequency ultrasonic, and pressure sensing. As a result, the system is able to detect gestures such as squeezing, swiping, and knocking. In one of the use cases, the dome structure is able to roll windows up in response to an input gesture. These fabrication techniques show that air pouches are scalable, flexible, and able to withstand considerable force, ultimately allowing for the pouches to be exploited in both active and passive manners.

Air pouches have also recently been exploited for adding interactive input to handheld devices using acoustic sensing techniques. Laput et al. [5] propose a novel method to sense an end user's hand-touch gestures by classifying audio signals generated from the deformation of the air pouches. Using a speaker-microphone pathway to release ultrasonic frequency sweeps and record audio, the captured signals are converted to the frequency domain using a Fast Fourier Transform (FFT) and fed into a support vector machine (SVM) for classification. From classification, different signals can be distinguished from one another, allowing for touch sensitive user input.

This form of sensing was also used by Swaminathan et al. [9] to add interactivity in the pneumatic structures previously described.

He et al. [6] build on the work of Laput et al. [5] and present a very similar method to enable interactivity through using a microphone and corrugated tubes to classify air pulses generated from squeezing a soft cavity. Through investigating the effects of varying the shape of corrugated tubes, they were able to discover several design implications of the tubes during the classification of air pulses. These will be helpful for maximizing classification accuracy while selecting tubes for our foot wearable. We used the same method provided by Laput et al. [5] in order to detect the air pouch's deformation in real-time. This acousting sensing method will increase the interactivity of the wearable and allow the end-user to perform both passive and active tasks.

Methodology

To begin air pouch fabrication, we followed the method presented by Niyama et al. [7] to create air pouches. In order to easily create pouches of different shapes, we constructed a gantry system to automate precise fabrication. Using the kit for a Prusa i3 Mk3 3D printer, we built a fabrication machine that uses a standard soldering iron in place of the extruder. The machine proved to be much more reliable than soldering by hand, as it was able to apply the correct constant pressure to the thermoplastic sheets to provide a quality sealing. We used the Repetier-Host application to manage fabrication and write G-code, a machine programming language, to control the movement of the soldering iron. After proper configuration of important parameters such as z-axis height, feed rate, and air pouch entrance dimension, we were able to construct air-tight sealed air pouches.

In order to further accelerate the fabrication process, we decided to make a graphical user interface (GUI) to quickly generate G-code for air pouches of different sizes. The GUI supports the use of horizontal and vertical lines to design the air pouch, and the user can easily specify the location on the bed for the machine to heat bond the thermoplastic sheets together. One of the limitations of the GUI is that maneuvers such as splines are not supported, so we found an alternative method in order to generate the G-code for more complex air pouch shapes. We used Adobe Illustrator, a well known vector graphics editor, to design air pouches with curve shapes and an intermediate file conversion tool to convert the file into an stl file, which is compatible with Repetier Host's Slic3r tool. Slic3r is a 3D slicing engine for 3D printers that generates G-code from CAD (Computer Aided Design) files, and we used it to slice the one layer necessary to construct an air pouch. After some cleanup of the resulting G-code, we were able to create more complex shapes. Since we may want to use a more sophisticated design similar to the previously mentioned Reebok's InstaPump shoes, the ability to generate G-code for spline maneuvers is critical to the final design of the foot wearable’s air pouches.

For pneumatic actuation, we used a simple system involving an Arduino microcontroller, air pump, vacuum, and series of tubes to inflate and deflate the air pouches. The system is also very flexible, as we can use multiple air tube channels in order to inflate and deflate more than one air pouch at a time. We can also configure the control logic to inflate and deflate the air pouches together or inflate one air pouch while deflating the other air pouch. Such a system can provide haptic feedback to the user in various ways, especially if multiple air pouches are used in the final design of the foot wearable.

As for acoustic sensing, we followed the method presented by Laput et al. [5] to sense the inflation and deflation of an air pouch using a speaker and microphone. We attached the microphone onto an air pouch and the nearby speaker emitted a continuous ultrasonic sweep. In turn, the microphone monitored the output and recorded audio signals. After converting the captured audio signals into the frequency domain using a FFT and feeding these audio signals into an SVM for training, we were able to classify when the air pouch is partially inflated, fully inflated, or deflated. From here, we are able to detect differences in a user’s unique deformation of the air pouches and use this additional interactivity to help the user perform tasks.

Results

Upon following the air pouch fabrication method presented by Niiyama et al. [7] to create air pouches, we found that the machine is able to produce high quality sealings to the air pouches consistently. The resulting air pouches proved to be much better than ones we made by hand using a soldering iron, as the machine can be easily tuned to find the right pressure and consistently apply such pressure to the thermoplastic sheets. We found our own methods to generate the G-code necessary to control the machine's movement to generate air pouches of various shapes. Using our own air pouch GUI, we were able to create very simple air pouches made from only horizontal and vertical straight lines. The user is able to specify the exact location on the bed of the machine for the air pouches to be constructed. This proved to be especially convenient and efficient, allowing the pouches to be constructed sequentially anywhere on the bed every 7-8 minutes. However, the support of more complex shapes is critical to the final design of the wearable's air pouches. So, our other technique consisted of using multiple tools, including Adobe Illustrator, an intermediate 3rd party file conversion tool, Slic3r, Repetier Host, and Python script for G-code cleanup in order to create air pouches of any shape. While this alternative does take slightly longer to fabricate air pouches, we found this to be a critical component of the final design of the air pouches we will use on the foot wearable.

For pneumatic actuation of the air pouches, we developed a flexible system that allows for rapid inflation and deflation. Using an Arduino microcontroller, air pump, vacuum, and series of tubes, we were able to inflate and deflate the air pouches. Through multi-channel air tube controls, the system is also able to support inflation and deflation of one or two air pouches, which allows for further flexibility in the design and use cases of the wearable. We found that it takes around 1.5-2 seconds for inflation and 2-2.5 seconds for deflation of each air pouch, which are pretty close to what we are shooting for. The more rapid we can make the inflation and deflation, the more noticeable and convenient for the user.

As for acoustic sensing, we experimented with the same method presented by Laput et al. [5] in order to detect differences in the air pouch's inflation and deflation. Using an SVM to classify whether the air pouch was partially inflated, fully inflated, or deflated, we found that the classification accuracy was suboptimal. In our basic setup, the speaker was placed near the air pouch and the microphone was on top of the air pouch. However, the classifier failed to consistently distinguish between the different levels of inflation after several training runs. This leads us to experiment with other setups with the microphone placed inside the air pouch to successfully capture audio output signals or search for alternative sensing methods that work better for our system.

Conclusion and Future Direction

We made considerable progress towards finishing constructing a foot wearable that uses a pneumatic actuation system to inflate air pouches in order to provide a tightening sensation to the user. Once we are able to start working on the physical implementation of our wearable again, we will attach the air pouches and pneumatic actuation system to a shoe. From there, we will iteratively adjust our air pouch design for the system to work as best as it can. Ultimately, we would like inflation and deflation of the air pouches to work as fast as possible in order to increase the noticeability for the user, as we are headed towards shaping the direction of the project more towards the wearable acting a tangible interface for haptic feedback rather than using acoustic sensing methods to add interactive input to our wearable.

In the cybersecurity realm, using tangible interfaces as a medium for users to make cybersecurity-related decisions is a relatively unexplored area. For example, when a user walks into a physically unsafe area or an area with a lot of unsecure wifi connections, the wearable can deflate to notify the user of this change. Today, users often are desensitized to notifications on devices such as phones and watches since they get them so often. Using tangible interfaces as a medium from the digital to the physical world to inform the user of some critical information may solve this issue.

References

[1] Park, Yong-Lae, et al. "Design and control of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation." *Bioinspiration & biomimetics* 9.1 (2014): 016007.

[2] [n. d.]. Smartwatches - Statistics Facts. https://www.statista.com/topics/4762/smartwatches/. Accessed: 2019-05-02

[3] Myers, Casey A., et al. "Motorized self-lacing technology reduces foot-shoe motion in basketball shoes during dynamic cutting tasks." *Footwear Science* 11.sup1 (2019): S189-S191.

[4] “Bodega's UnOfficial History Of The Reebok PUMP.” *Bodega*, https://bdgastore.com/blogs/blogdega/15702348-bodegas-unofficial-history-of-the-reebok-pump.

[5] Laput, Gierad, et al. "Acoustruments: Passive, acoustically-driven, interactive controls for handheld devices." *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2015.

[6] He, Liang, et al. "SqueezaPulse: Adding Interactive Input to Fabricated Objects Using Corrugated Tubes and Air Pulses." *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2017.

[7] Niiyama, Ryuma, et al. "Sticky actuator: Free-form planar actuators for animated objects." *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2015.

[8] Sareen, Harpreet, et al. "Printflatables: printing human-scale, functional and dynamic inflatable objects." *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 2017.

[9] Swaminathan, Saiganesh, et al. "Input, Output and Construction Methods for Custom Fabrication of Room-Scale Deployable Pneumatic Structures." *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 3.2 (2019): 62.